Photoelastic imaging of laser generated surface acoustic waves

H. Yamazaki,1 O. Matsuda,1 J. J. Baumberg,2 and O. B. Wright1

1Department of Applied Physics, Faculty of Engineering, Hokkaido University, Sapporo, Japan
2Department of Physics and Astronomy, University of Southampton, Southampton, UK
E-mail: hirotoy@eng.hokudai.ac.jp

Abstract
Surface acoustic wave (SAW) imaging is very useful for testing thin structures, in particular because it allows film thicknesses or elastic constants to be derived. In the past, non-contact SAW measurement has often been achieved with pulsed-laser acoustics by the use of optical pulses of picosecond to nanosecond duration. Here we present a method for imaging SAW based on optical reflectivity measurements combined with excitation using picosecond optical pulses. The SAW are generated in a thin aluminium film on a transparent glass substrate. The SAW acoustic strain modulates the refractive index of the film and substrate through the photoelastic effect. Probe laser pulses incident from the film or substrate side can be used to image the SAW propagation in real time by simply monitoring the modulation in the reflected probe beam intensity. By tightly focusing the excitation and probe beams we obtain a lateral spatial resolution of a few microns together with picosecond temporal resolution. When we image from the substrate side a surface-skimming bulk wave is clearly imaged in addition to the SAW.

1. Introduction
The imaging of surface acoustic waves is widely used to nondestructively test thin films and microstructures or to study elastic, piezoelectric or thermal properties. Various optical methods for all-optical SAW imaging have been proposed [1, 2]. Recently we introduced an imaging method for SAW in the MHz-GHz range based on the use of ultrashort optical pulses combined with interferometric detection [3]. This method involves the monitoring of the optical phase change arising from the surface displacement associated with the SAW. The dispersion relation of the SAW can be derived directly from SAW images for isotropic or anisotropic samples; the phonon focusing patterns arising from anisotropy in crystals show complex cuspidal features, but the use of spatial and temporal Fourier image processing allows the extraction of the dispersion relations for individual modes [4].

Here we present a new method for the imaging of SAW with ultrashort optical pulses that makes use of the photoelastic effect as the detection mechanism. After generation of the SAW with an picosecond optical pulse, the acoustic strain of the SAW is detected through the change in reflectivity of a probe optical pulse. This reflectivity change arises from the change in the refractive index of the sample owing to the photoelastic effect. Similar effects have been used to detect bulk acoustic waves with ultrashort optical pulses [5]. The probe optical beam spot is scanned over the sample surface to form an image at a given time delay between the two optical pulses, and the process is repeated to form an animation of the SAW propagation in real time. This photoelastic detection scheme is sensitive to strain components not detectable by surface displacement measurements.

2. Experimental setup
Our experimental setup is shown in Fig. 1, making use of the optical pump and probe technique, as explained below. The sample is a thin polycrystalline aluminium film 70 nm in thickness on a crown glass substrate of thickness 1 mm. Sub-picosecond duration optical pulses of central wavelength 830 nm, repetition rate 80 MHz and incident average power ~40 mW from a mode-locked Ti:sapphire pulsed laser are focused to a circular ~2 \( \mu \)m diameter spot on the sample using a \( \times 100 \) microscope objective lens at normal incidence. The excitation (pump) pulses are first incident from the transparent side of the sample (as shown in Fig. 1). A second set of measurements is taken with the sample inverted so that the probe beam is incident from the transparent side. The pump pulse absorption in the metal film produces acoustic fields through the thermoelastic effect composed of SAW and bulk waves. The wavelength of the SAW is governed by the lateral spot size of the pump beam and by thermal diffusion. The broadband SAW pulse has an acoustic wavelength ~10 \( \mu \)m. Normally-incident temporally-delayed sub-picosecond probe pulses of wavelength 415 nm and incident average power ~3 mW are generated by an optical second harmonic generation crystal. These pulses are used to detect the reflectivity changes of the sample through the photoelastic effect. The circularly polarized probe beam is focused to a ~2 \( \mu \)m diameter spot on the sample using a \( \times 50 \) microscope objective lens mounted on a scanning stage. For a fixed optical delay time between pump and probe optical pulses, we raster scan the probe beam spot laterally to produce an
image. This typically takes 15 min for a 100×100 pixel image. Chopping the pump beam at 1 MHz and using lock-in detection allows changes in relative reflectivity as small as 2×10⁻⁷ to be resolved. The typical relative reflectivity changes observed were ~10⁻⁶.

**Figure 1**: Experimental setup for the SAW imaging. PBS and QWP stand for polarizing beam splitter and quarter-wave plate, respectively.

### 3. Results and discussion

Figure 2 shows typical experimental images obtained over an 80 μm × 80 μm region at a time ~7 ns after the optical pump pulse arrival at the centre of the images. Figure 2(a) corresponds to an image probed from the Al film side and 2(b) to an image probed from the substrate side. The elastic waves appear as the dark or light areas. The features in the centre of the images are caused by the temperature rise induced by the pump pulses. In the image probed from the Al film side [Fig. 2(a)] the SAW produce a circular ring characteristic of the substrate and film isotropy. The SAW velocity of Al and crown glass are nearly equal (2700 ±100 ms⁻¹) and the Al thickness is very thin compared with the SAW wavelength so that there is little evidence of the pulse-broadening effects of acoustic dispersion. For normally-incident probe light the photoelastic effect couples the reflectivity to the η_xx, η_yy, and η_zz components of the strain tensor η_{ij}. In the case of probing from the glass substrate side [Fig. 2(b)], a surface-skimming bulk longitudinal wave (SSBW) is also clearly observed in addition to the SAW. The outer ring corresponds to the SSBW (longitudinal sound velocity in crown glass = 5090 ms⁻¹) and the inner ring to the SAW. Both the SAW and the SSBW show a characteristic symmetrical pattern in spite of the sample being elastically isotropic. These patterns are only seen when probing from the glass substrate side. Possible explanations for this pattern are as follows. (i) Owing to the penetration (~10 μm) of the acoustic strain into the substrate, the strain distribution acts locally like a transient cylindrical lens that distorts the reflected probe beam shape. Such lensing effects are well known in photothermal experiments [6]. If on exiting the objective lens system the probe beam is clipped by part of the lens aperture, a pattern with symmetry similar to that seen could be produced. (ii) Another possibility is a residual elliptical polarization of the probe beam. More experiments are underway to pin down the cause of this effect.

### 4. Conclusions

In conclusion, we have demonstrated the feasibility of real-time SAW imaging with reflectivity measurements using an ultrashort-pulse optical technique. Surface acoustic waves and surface skimming longitudinal bulk waves were observed on an aluminium polycrystalline film sample. The simplicity of the detection scheme makes these measurements particularly straightforward. Further work is required to understand the origin of the signals observed for probe incidence from the transparent substrate side. In future, by using a probe beam at non-normal incidence it should be possible to obtain information on the shear components of the strain tensor, and to reveal acoustic modes not otherwise optically accessible in anisotropic materials.

### 5. Acknowledgements

We thank Yoshihiro Sugawara for fruitful discussions and help in the experiment.

### 6. References